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MINIMUM DETECTABLE CONCENTRATIONS AND WAC TRIGGER LEVELS FOR THE IN SITU NaI GAMMA SPECTROSCOPY SYSTEMS USED AT THE FERNALD ENVIRONMENTAL MANAGEMENT PROJECT

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LIST OF ACRONYMS AND ABBREVIATIONS

EMS	Excavation Monitoring System
FEMP	Fernald Environmental Management Project
FRL	final remediation level
L_C	critical level
L_D	detection limit
HPGe	high-purity germanium (detector)
MDC	minimum detectable concentration
NaI	sodium iodide (detector)
pCi/g	picoCuries per gram
ROI	region of interest
RSS	Radiation Scanning System
RTRAK	Radiation Tracking System
WAC	waste acceptance criteria

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DEFINITION OF SOME TECHNICAL TERMS

Variance. For a set of values, the average of the squares of the deviations of the values from the mean of the values.

Standard deviation. The positive square root of the variance.

Covariance. For two sets of values, the average of the sum of the products of the deviations of the corresponding values in the two sets from their respective means. The covariance is a measure of how strongly the values in the two sets are correlated. (The correlation between the two sets is defined as the covariance between the two sets of values divided by the product of the standard deviations of the two sets.)

Count. A discrete response of an instrument (a signal) resulting from the interaction of a photon with a detector.

Count rate. Number of counts per unit time.

Critical level (L_C). The net response level (net counts above background) at which the detector output can be considered "above background." It is the lower bound on the 95% detection interval defined for detection limit and is the level at which there is a 5% chance of erroneously calling a background value greater than background. (MARSSIM 2000, Section 6.7.1)

Detection limit (L_D). The net response level (net counts above background) that can be expected to be seen with a detector 95% of the time. It is an *a priori* estimate of the detection capability of a measurement system and is the level at which there is a 5% chance of erroneously considering a detector's response to be background when radioactivity is actually present at levels above background. (MARSSIM 2000, Section 6.7.1)

a priori. As applied to measurements, *a priori* quantities are values that are used before any measurements are actually made in order to estimate the capability of a particular approach.

Minimum detectable concentration (MDC). The detection limit multiplied by an appropriate conversion factor to give units of activity. It is the *a priori* net activity level above the critical level that an instrument can be expected to detect 95% of the time. The MDC should be used when giving the detection capability of an instrument. (MARSSIM 2000, Section 6.7.1)

Trigger level. A specified radionuclide concentration that, if exceeded by a measurement, provides the basis for some subsequent action to be taken. (DOE 1998)

Poisson distribution. A probability distribution commonly used to model radioactive decay. The distribution has the property that its mean and variance are equal.

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Signal. An instrument output; a meter reading. As used in this report, a signal is always an instrument output in counts.

Blank. The signal that results from a sample that is identical in principle to the sample of interest except that the substance to be measured is absent (or small in quantity compared to the uncertainty in the blank). (Currie 1968)

Well-known blank. A blank for which many measurements have been made and for which, as a consequence, the uncertainty in its average value is small.

Gross signal. An instrument output including the blank.

Net signal. An instrument output relative to the blank (i.e., gross signal - blank).

Region of interest (ROI). A range of channels (gamma energies) established to include a spectral peak related to the isotope of interest.

Background regions. A number of channels (gamma energies) established adjacent to (above and below) the ROI. These regions are used to estimate the response expected in the ROI in the absence of any contribution from the isotope of interest.

SUMMARY

The availability of the calibration pad at the Fernald Environmental Management Project (FEMP) has allowed improved calibrations to be developed for the sodium iodide (NaI) detectors used in the mobile in situ gamma spectroscopy systems that the FEMP deploys for scanning soils for radionuclides. Availability of the pad also has allowed the determination for those systems of (1) improved trigger levels for use in establishing whether soil exceeds the waste acceptance criterion (WAC) for uranium for the FEMP's on-site disposal facility and (2) improved minimum detectable concentrations (MDCs).

The WAC trigger levels for all the NaI systems currently in service (RTRAK, RSS1, RSS2, and EMS) are well above the minimum acceptable trigger level of 721 ppm. The trigger levels vary from 820 to 860 ppm.

To allow the reliable detection of hot spots, the MDCs for NaI measurements should be less than about three times the relevant final remediation level (FRL). All systems currently in service have MDCs below or approximately equal to three times the FRLs for uranium (82 ppm) and Th-232 (1.5 pCi/g) for two aggregated four-second measurements. For Ra-226, the MDCs are below three times the FRL (1.7 pCi/g) when five to seven 4-s measurements are aggregated.

Although some inter-platform variability is observed in MDCs (largely due to differences in calibration coefficients), the results indicate that the detectors in all the systems behave similarly.

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1.0 INTRODUCTION

Availability of a calibration pad has allowed improved calibrations of the sodium iodide (NaI) detectors in the mobile in situ gamma spectroscopy systems used for scanning soil for U-238, Th-232, and Ra-226 isotopes at the Fernald Environmental Management Project (FEMP) (DOE 2001). The more reliable counting data and the improved calibrations that have been obtained using the pad also have allowed the determination of more reliable trigger levels and minimum detectable concentrations (MDCs) for the systems, which are presented in this report. Results are provided for the RTRAK, RSS1, RSS2, and EMS. No results are included for the Gator, which is being modified to accommodate a rear-mounted detector. Results for the Gator will be provided separately.

Trigger levels are considered in Section 2 and minimum detectable concentrations are discussed in Section 3. Conclusions are given in Section 4. Major technical background, derivations, data, and example calculations are given in the appendices.

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2.0 TRIGGER LEVELS FOR URANIUM WASTE ACCEPTANCE CRITERION

As defined in the User Guidelines (DOE 1998), a trigger level is a specified radionuclide concentration that, if exceeded by a measurement, provides the basis for some subsequent action to be taken. Trigger levels are used because of the uncertainty associated with measurements and are set below the relevant regulatory limit to reduce the chance of erroneously classifying soil as meeting the limit when it actually does not. As discussed in the User Guidelines, minimum acceptable trigger levels are 70% of the regulatory limit.

This section considers the use of trigger levels for the NaI systems when determining whether soil exceeds the waste acceptance criterion (WAC) for uranium for the FEMP's on-site disposal facility, which is 1030-ppm total uranium. The minimum acceptable trigger level therefore is 721 ppm (DOE 1998).

The WAC trigger level is defined as

$$\text{Trigger} = L - k\sigma_{WAC} \tag{2-1}$$

where Trigger = the WAC trigger (ppm),

L = 1030 ppm (the uranium WAC),

k = a quantile of the normal distribution, selected to provide an acceptable level of confidence that a measurement below the trigger actually corresponds to soil with a uranium concentration below 1030 ppm,

and σ_{WAC} = the standard deviation in the measured uranium concentration at 1030 ppm.

To provide a 95% level of confidence, k is 1.645. With the uranium sources in the calibration pad, the effective uranium concentration of the pad is 993 ppm, as measured with an HPGe detector, and about 980 ppm, on the basis of theoretical calculations (DOE 2001). These two results are consistent and very near the WAC of 1030 ppm. Therefore, using results obtained from measurements on the pad with uranium sources in place, the standard deviation in the measured uranium concentration should be very near the standard deviation at the WAC level.

The calculation of σ_{WAC} is discussed in Appendix A for the NaI systems. The determination of σ_{WAC} considered only the variability due to counting errors. Other factors (e.g., soil moisture) also contribute random errors to measurements, but their effects were not considered in the determination of the value of σ_{WAC} used to obtain WAC trigger levels. Systematic errors associated with calibration also were not considered when determining σ_{WAC}. Such an approach is consistent with that used for the FEMP's HPGe detectors. The results for σ_{WAC} and WAC triggers for a single 4-s measurement are summarized in Table 2-1.

As shown in Table 2.1, all of the systems have trigger levels that are well above the minimum acceptable level of 721 ppm. The triggers vary from a high of about 860 ppm for the RSS2 to a low of about 820 ppm for the EMS.

An example calculation of a WAC trigger is provided in Section D.1 of Appendix D.

Table 2-1. σ_{WAC} and Trigger Levels for Uranium WAC[a]

	System			
Quantity	RTRAK	RSS1	RSS2	EMS
σ_{WAC} (ppm)	106.9	109.1	102.2	130.0
WAC trigger level[b] (ppm)	850	850	860	820

[a]Basis: The method used is given in Appendix A. The data used are given in Appendix C. Results are for a single 4-s measurement.

[b]Results rounded to two significant figures.

3.0 MINIMUM DETECTABLE CONCENTRATIONS

A minimum detectable concentration (MDC) is an *a priori* estimate of the minimum net activity level that can be measured reliably by a particular system or technique under a given set of conditions. MARSSIM (2000) defines it as the net activity level that can be expected to be detected 95% of the time. The MDC is determined from a detection limit (L_D), the net response level (counts relative to a blank or background) that is an *a priori* estimate of the detection capability of a measurement system (MARSSIM 2000), using factors to convert to units of activity. MDCs and L_Ds are accepted quantities for specifying detection sensitivities.

The approach used for determining detection limits for the NaI systems is given in Appendix B. Using the detection limits with the calibration equations for the systems provides MDCs. The calibration equations for the NaI systems for U-238, Ra-226, and Th-232 can be written as follows (DOE 2001):

$$U = F_1 U_{NCR} + F_2 Ra_{NCR} + F_3 Th_{NCR}$$

$$Ra = F_4 U_{NCR} + F_5 Ra_{NCR} + F_6 Th_{NCR}$$

$$Th = F_7 U_{NCR} + F_8 Ra_{NCR} + F_9 Th_{NCR}$$

where U, Ra, and Th are concentrations in pCi/g, U_{NCR}, Ra_{NCR}, and Th_{NCR} are raw (i.e., not corrected for interference from the other radionuclides) net count rates for the particular radionuclides, and F_1-F_9 are the calibration coefficients. The calibration coefficients for the systems are given in Table C-1 in Appendix C. The net count rates are relative to counts in the background regions associated with the region of interest (ROI) for the radionuclide, with an adjustment made for differences in the number of channels in the ROI and the background regions. (ROIs, background regions, and determination of net counts are discussed in Appendix B.)

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MDCs were determined with the above equations using the net count rate for the radionuclide of interest that corresponds to the detection limit for that radionuclide for various acquisition periods. The net count rates for the other radionuclides were assumed to be equal to the values obtained on the calibration pad when no sources are present. Counting results for each of the systems with no sources in place are given in Table C-3 in Appendix C for a 300-s acquisition period. When MDCs were determined, counts were adjusted to correspond to the acquisition period being considered.

Results of MDC calculations are summarized in Table 3-1 for total uranium (total uranium concentration in ppm equals three times the U-238 concentration in pCi/g), Ra-226, and Th-232. The table provides MDCs, along with values of the critical level (L_C) and L_D for the systems (the latter two values were determined for a 4-s acquisition period). L_C is defined as a net response level (relative to a blank or background) at which a detector output can be considered "above background" (MARSSIM 2000); see Appendix B for a more quantitative definition. MDCs were calculated assuming a typical moisture level (26%). To put the results for the MDCs in context, the table includes multiples of the final remediation levels (FRL) for the radionuclides (3×FRL). To allow reliable detection of hot spots, the MDCs should be less than the corresponding value of 3×FRL. To allow comparison with MDCs developed before the use of the calibration pad, the table includes the MDCs for the RTRAK platform that are given in the User Guidelines (DOE 1998).

All four of the platforms have MDCs for uranium and Th-232 less than or approximately equal 3×FRL when two 4-s measurements are aggregated. For Th-232, the MDCs for all four platforms for a single 4-s measurement are well below 3×FRL. For Ra-226, the MDCs for a two aggregated, 4-s measurements are well above 3×FRL for all platforms. A total count time of about 20 s (five aggregated 4-s measurements) is needed to achieve an MDC for Ra-226 below 3×FRL for most of the platforms. For the RSS1, a 28-s count is needed. MDCs are a function of moisture level and are lower at levels of moisture lower than the typical value used in obtaining the results shown in Table 3.1.

The MDCs for the RTRAK for uranium and especially Ra-226 are considerably larger than those presented in the User Guidelines. The increase for uranium results primarily from the use of improved calibration equations that have been developed using the calibration pad. The improved calibration is discussed in DOE (2001). For Ra-226, the increase results primarily from the use of a Ra-226 correction (DOE 1998) when determining the MDC. (A Ra-226 correction is necessary to address the loss of Rn-222 from soil, which affects the results of the measurement of the concentration of Ra-226 made by the NaI systems.)

The approach used in Appendix B to determine MDCs considers the variation in the counts in the background regions as the concentration of the radionuclide of interest varies. The relationship between such background counts and net counts is approximately linear (Appendix B, Figure B-2). Detection limits determined with Currie's (1968) widely used Eq. 13 (equivalent to Eq. 6-6 in MARSSIM) are somewhat lower than those obtained considering variations in counts in the background region. For example, for the RTRAK for 4-s measurements, Currie's approach yields detection limits of 80.7 and 99.5 counts for uranium and Ra-226, respectively; the approach used in Appendix B yields values of 86.0 and 122.6 counts (see Table 3-1). As a result, the MDCs presented in this report are somewhat larger than those that are obtained with a simple application of Currie's approach.

The calculated detection limits are relative to the "blank" – which corresponds to the background concentration in the pad soil. These concentrations are 0.45 pCi/g for Th-232 and 0.51 pCi/g for Ra-226, on the basis of HPGe measurements made on the pad (see DOE 2001, for example, Table 4-2). The uranium concentration in the pad soil cannot be determined with the HPGe systems, which have an MDC for uranium of about 5.8 ppm for a 900-s count (DOE 1998, Table 5.1-1). The concentration of uranium in the pad soil (less than about 6 ppm) is a negligible fraction of the MDCs estimated for the NaI systems (less than about 3% for an 8-s MDC). Also, the concentration of Ra-226 in the pad soil is a negligible fraction of the MDCs for Ra-226 (less than or approximately equal to 10% for counting periods up to 20 s). However, the Th-232 concentration in the pad soil is a sizeable fraction of the MDCs for Th-232 (about 30% of the 4-s MDC). Therefore, the MDCs for Th-232 given in Table 3.1 likely underestimate the actual 4-s MDCs for Th-232 by about 23% (i.e., if the actual MDC is 30% larger than the estimate, then the estimate is 23% below the actual value). However, given that the MDCs for Th-232 are well below 3×FRL, the underestimate is of little practical significance. The influence of the levels of uranium and Ra-226 in the pad soil on the actual MDCs for uranium and Ra-226 is likely to be negligible.

Example calculations for L_C, L_D, and an MDC are given in Section D.2 of Appendix D.

TABLE 3-1. Results of MDC Calculations[a]

Quantity[b]	RTRAK	RSS1	RSS2	EMS
	Uranium			
L_C	39	41	41	39
L_D	86.0	90.5	90.0	88.8
MDC (4 s)	337	345	306	383
MDC (8 s)	234	239	207	258
MDC (12 s)	191	194	165	206
3×FRL	246	246	246	246
Former MDC (4 s)[c]	247	NA	NA	NA
	Ra-226			
L_C	48	52	53	48
L_D	122.6	127.1	126.6	118.2
MDC (4 s)	18.4	22.2	17.1	17.9
MDC (8 s)	9.8	12.1	9.5	9.7
MDC (12 s)	7.1	8.8	6.9	7.0
MDC (20 s)	4.9	6.1	4.9	4.9
3×FRL	5.1	5.1	5.1	5.1
Former MDC (4 s)[c]	2.5	NA	NA	NA
	Th-232			
L_C	25	28	28	28
L_D	56.9	62.1	62.9	62.7
MDC (4 s)	1.6	1.5	1.6	1.6
MDC (8 s)	1.1	1.0	1.1	1.1
MDC (12 s)	0.9	0.8	0.9	0.9
3×FRL	4.5	4.5	4.5	4.5
Former MDC (4 s)[c]	1.4	NA	NA	NA

(Columns RTRAK, RSS1, RSS2, EMS are grouped under "System".)

[a]Basis: L_C and L_D were determined as described in Appendix B (background counts not constant, blank not well known). The calibration coefficients used to determine the MDCs are given in Appendix C. Measurement times of 4 s were used (8 s indicates the aggregation of two 4-s measurements, 12 s the aggregation of three 4-s measurements, etc.). MDCs are dry-weight concentrations. A moisture correction factor of 1.26 was used. The Ra-226 MDC has a Ra-226 correction (DOE 1998) applied, except as noted.

[b]Units: L_C and L_D are in counts per 4 s. MDCs and FRLs are in pCi/g, except for uranium (ppm).

[c]DOE (1998), Table 5.1-4 (provides MDCs for the RTRAK only). Values were converted to dry-weight concentrations for this table using a moisture correction factor of 1.26. No Ra-226 correction was applied.

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4 CONCLUSIONS

1. There is little inter-platform variability (less than about 10%) among the NaI systems for L_C (critical level) and L_D (detection limit). Inter-platform variability for MDCs for uranium and Ra-226 is somewhat larger than for detection limits due to differences in calibration coefficients. Overall, the results indicate that the detectors in the systems behave similarly. (See Table 3.1.)

2. For typical levels of soil moisture, the MDCs for all platforms are less than or approximately equal three time the relevant FRL for two aggregated 4-s measurements for uranium and Th-232. For Ra-226, MDC < 3×FRL when five to seven 4-s measurements are aggregated. MDCs are a function of moisture level and increase as moisture level increases. (See Table 3.1.)

3. For intended applications at the FEMP, the presence of U-238, Ra-226, and Th-232 in the soil of the calibration pad has no practical significance for the determination of MDCs using the pad.

4. MDCs for the RTRAK are greater than the values given in the User Guidelines (DOE 1998). Changes are primarily the result of using improved calibration equations and consideration of a Ra-226 correction (i.e., accounting for Rn-222 loss from soil), which has a major influence on the MDC for Ra-226. (See Table 3.1.)

5. Adjusting the counts in the background regions at L_D to reflect increases expected above those observed for blank conditions, as was done in obtaining the MDCs given in Table 3.1, increases the MDCs for uranium, Ra-226, and Th-232 somewhat relative to assuming that no change occurs in the background regions as source concentrations increase.

6. The WAC triggers for all platforms are well above the minimum acceptable level of 721 ppm. (See Table 2.1.)

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U.S. Department of Energy, 1998, "User Guidelines, Measurement Strategies, and Operational Factors for Deployment of *In-Situ* Gamma Spectrometry at the Fernald Site," Fernald Area Office, July.

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APPENDIX A: DETERMINATION OF WAC TRIGGER LEVELS

A WAC trigger level is defined by the following equation, with k chosen to set the trigger level so that 95% of all measurements of soil having an actual uranium concentration of 1030 ppm will be above the trigger level:

$$\text{Trigger} = L - k\sigma_{WAC} \quad \text{(A-1)}$$

where Trigger = the WAC trigger (ppm),
L = 1030 ppm (the uranium WAC),
k = 1.645,
and σ_{WAC} = the standard deviation in the measured uranium concentration at 1030 ppm.

To determine the trigger, σ_{WAC} must be determined. Using the calibration equation for uranium (DOE 2001, Sect. 4) and converting to a uranium concentration in ppm (i.e., multiplying three times the U-238 specific activity in pCi/g):

$$U_{ppm} = 3\,[F_1\, U_{NCR} + F_2\, Ra_{NCR} + F_3\, Th_{NCR}]$$

where F_1, F_2, F_3 are calibration coefficents and
U_{NCR}, Ra_{NCR}, Th_{NCR} are raw (i.e., not corrected for interference from the other radionuclides) net count rates (counts/s) for U-238, Ra-226, and Th-232.

Neglecting any covariances between the net count rates and also any systematic uncertainty in the calibration coefficients, the variance in the uranium concentration is

$$\sigma_{Uppm}^2 = 9\,[F_1^2\, \sigma_{UNCR}^2 + F_2^2\, \sigma_{RaNCR}^2 + F_3^2\, \sigma_{ThNCR}^2] \quad \text{(A-2)}$$

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For the NaI systems, net counts for a radionuclide are determined by obtaining the total (gross) counts in the region of interest (ROI) for the radionuclide and then subtracting the counts in the background regions, adjusted for the difference in the number of channels in the background and ROI (DOE 2001):

$$N = G - \frac{n_1}{n_2} BG$$

where N = net counts (for the radionuclide of interest),
G = gross counts (in the ROI),
BG = counts in the background regions associated with the ROI,
n_1 = number of channels in the ROI, and
n_2 = total number of channels in background regions (both sides of ROI).

The net count rate is NCR = N/T_0, where T_0 is the time interval for which the counts were determined (live time). The variance in the net count rate is

$$\sigma_{NCR}^2 = \frac{1}{T_0^2} [\sigma_G^2 + \left(\frac{n_1}{n_2}\right)^2 \sigma_{BG}^2]$$

where any uncertainty in T_0 is neglected. Assuming that the counts have a Poisson distribution (for which the mean and variance are equal),

$$\sigma_{NCR}^2 = \frac{1}{T_0^2} [\mu_G + \left(\frac{n_1}{n_2}\right)^2 \mu_{BG}]$$

where the μ's are the means of the respective counts in the time period T_0.

If the mean counts were determined for some period T_1 other than T_0, then the variance in the net count rate for the time period T_0 is given by

$$\sigma_{NCR}^2 = \frac{1}{T_0^2}[\frac{T_0}{T_1}\mu_G + \frac{T_0}{T_1}\left(\frac{n_1}{n_2}\right)^2\mu_{BG}]$$

Therefore,

$$\sigma_{NCR}^2 = \frac{1}{T_0 T_1}[\mu_G + \left(\frac{n_1}{n_2}\right)^2\mu_{BG}]$$

To simplify the equation, let $V = \mu_G + \left(\frac{n_1}{n_2}\right)^2\mu_{BG}$

Then

$$\sigma_{NCR}^2 = \frac{V}{T_0 T_1} \qquad \text{(A-3)}$$

Using Eq. A-2 and A-3,

$$\sigma_{Uppm}^2 = 9\,[F_1^2\frac{V_U}{T_0 T_1} + F_2^2\frac{V_{Ra}}{T_0 T_1} + F_3^2\frac{V_{Th}}{T_0 T_1}] \qquad \text{(A-4)}$$

where the quantities V_U, etc. are determined using the average counts for time period T_1. σ_{Uppm}^2 applies to the time period T_0.

From Eq. A-4, the standard deviation in the uranium concentration (in ppm) is

$$\sigma_{Uppm} = \frac{3}{\sqrt{T_0 T_1}}\,[F_1^2 V_U + F_2^2 V_{Ra} + F_3^2 V_{Th}]^{0.5} \qquad \text{(A-5)}$$

When the standard deviation is obtained at the uranium WAC level (1030 ppm) using Eq. A-5 (i.e., $\sigma_{WAC} = \sigma_{Uppm}$), the result can be substituted into Eq. A-1 to give the WAC trigger. If net counts were determined for a 300-s period and a trigger is needed for a 4-s period, $T_0 = 4$ and $T_1 = 300$.

Using the data provided in Appendix C, trigger levels can be determined for the NaI systems. Results are given in Table A-1, which also shows the calculated variances and the standard deviation in the measured uranium concentration at the WAC level.

An example calculation for the RTRAK is provided in Section D.1 of Appendix D.

Table A-1. Variances for Isotopic Net Count Rates and Determination of the WAC Trigger for a 4-s Count[a]

	System			
Quantity[b]	RTRAK	RSS1	RSS2	EMS
σ_{UNCR}^2	77.1	82.8	81.6	84.6
σ_{RaNCR}^2	42.1	48.6	50.9	47.3
σ_{ThNCR}^2	8.2	9.3	9.6	9.9
σ_{Uppm}^2	11425.8	11908.2	10443.8	16893.2
σ_{WAC}	106.9	109.1	102.2	130.0
WAC trigger level	854	851	862	816

[a]Basis: σ_{UNCR}^2, σ_{RaNCR}^2, and σ_{ThNCR}^2 were calculated using Eq. A-3; σ_{Uppm}^2 was calculated using Eq. A-4 (or, equivalently, A-2). σ_{WAC} was determined using Eq. A-5. The WAC trigger was determined with Eq. A-1. Counting data obtained with the sources in the pad, the calibration coefficients, and the number of channels are given in Tables C-3, C-1, and C-2, respectively, in Appendix C.

[b]Units: σ_{UNCR}^2, σ_{RaNCR}^2, and σ_{ThNCR}^2 are in (counts/s)^2. σ_{Uppm}^2 is in ppm^2. σ_{WAC} and the WAC trigger have units of ppm.

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APPENDIX B: DETERMINATION OF DETECTION LIMITS

In determining a detection limit one considers the net signal, which is the gross signal less the blank:

$$S = (S + B) - B$$

where S + B is the gross signal and B is the blank[*]. For NaI systems, the blank corresponds to measurements made on the pad with no sources in place (standards containing only pad soil are used), which can be considered to represent "background" conditions. The gross signal corresponds to measurements made with some sources present.

The variance of the net signal is given by

$$\sigma_S^2 = \sigma_{S+B}^2 + \sigma_B^2$$

Let σ_0^2 be the variance of the net signal when only a blank is used (i.e., S = 0). Then, $\sigma_0^2 = \sigma_B^2 + \sigma_B^2 = 2\ \sigma_B^2$. (If many measurements have been made of the blank, it is called a "well-known blank" and the variance of the estimated average of the blank becomes small. In such cases σ_0^2 approximately equals σ_B^2, as opposed to $2\sigma_B^2$ when the blank is not well known.)

For the NaI systems one determines net counts. These counts are counts in the region of interest (ROI) less counts in the background regions associated with the ROI, adjusted for differences in the number of channels in the ROI and background regions. Figure B-1 shows a spectrum obtained with a NaI system, indicating the ROI and background

[*] The basic definitions used are taken from Currie ("Limits for Qualitative Detection and Quantitative Determination," *Analytical Chemistry*, 40 (3): 586-593, March 1968). A blank is defined by Currie as the signal that results from a sample that is identical in principle to the sample of interest except that the substance to be measured is absent (or small in quantity compared to σ_B). The blank does include the effects of interfering species.

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regions for U-238, Ra-226, and Th-232. The net counts for the system should not be confused with the net signal. Also, counts in the background regions should not be confused with net counts above background (i.e., net counts above the blank). Net counts for the NaI systems are given by the following (DOE 2001, Sect. A.5), as discussed in Appendix A:

$$N = G - \frac{n_1}{n_2} BG$$

where G = the total (gross) counts in the ROI,
BG = the counts in the background regions associated with the ROI,
n_1 = number of channels in the ROI, and
n_2 = number of channels in the background.

The variance of the net counts for the NaI systems is given by

$$\sigma_N^2 = \sigma_G^2 + \left(\frac{n_1}{n_2}\right)^2 \sigma_{BG}^2$$

The critical level, L_C, is defined as

$$L_C = k_\alpha \, \sigma_0$$

where k_α is the $(1 - \alpha)^{th}$ quantile of the standard normal distribution.

The *a priori* detection limit is defined as

$$L_D = L_C + k_\beta \, \sigma_D$$

where k_β is the $(1 - \beta)^{th}$ quantile of the standard normal distribution and σ_D is the standard deviation of the net signal when its actual value is L_D.

Let $k_\alpha = k_\beta = k = 1.645$ for this discussion. That is, the probabilities of type I and II errors are both assumed to be 0.05. Type I errors are false positives (i.e., a net response is considered to be above background when the true radionuclide concentration is below background levels). Type II errors are false negatives (i.e., a net response is considered to be at background when the true radionuclide level is above background).

Then, for the case in which the blank is not well know ($\sigma_0^2 = 2\,\sigma_B^2$),

$$L_C = k\,\sigma_0 = \sqrt{2}\;k\,\sigma_B$$

and

$$L_D = L_C + k\,\sigma_D$$

For the NaI systems, σ_B is the standard deviation of the net counts (net of counts in background regions) on the pad with no sources present (blank). This quantity is represented by σ_{N0}. (Similarly, σ_{ND} is the standard deviation of the net counts at the detection limit.)

Therefore,

$$L_C = \sqrt{2}\;k\,\sigma_{N0} \qquad \text{(B-1)}$$

$$= \sqrt{2}\;k\left[\sigma_{G0}^2 + \left(\frac{n_1}{n_2}\right)^2 \sigma_{BG0}^2\right]^{0.5}$$

The gross and background counts are assumed to have a Poisson distribution (for which the variance equals the mean). Therefore,

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$$L_C = \sqrt{2}\ k\ [\mu_{G0} + \left(\frac{n_1}{n_2}\right)^2 \mu_{BG0}]^{0.5} \qquad \text{(B-2)}$$

where the μ_{G0} = mean value for gross counts and μ_{BG0} = mean value for background counts, when no sources are present in the pad.

If many measurements of net counts are made with no sources present ("well-known blank"), $L_C = k\ \sigma_{N0}$.

Note that the variance of the net signal at the detection limit (σ_D^2) is given by

$$\sigma_D^2 = \sigma_{S+B}^2 + \sigma_B^2 = \sigma_{ND}^2 + \sigma_{N0}^2$$

Therefore, for the NaI systems,

$$L_D = L_C + k\ [\sigma_{GD}^2 + \left(\frac{n_1}{n_2}\right)^2 \sigma_{BGD}^2 + \sigma_{N0}^2]^{0.5}$$

where σ_{GD}^2 and σ_{BGD}^2 are the variances of the gross counts in the ROI and background regions, respectively, at the detection limit.

Also,

$$L_D = L_C + k\ [\mu_{GD} + \left(\frac{n_1}{n_2}\right)^2 \mu_{BGD} + \sigma_{N0}^2]^{0.5} \qquad \text{(B-3)}$$

For the NaI systems,

$$L_D = \mu_{ND} - \mu_B \qquad \text{(i.e., the net signal = gross signal – blank)}$$

$$= [\mu_{GD} - \frac{n_1}{n_2}\ \mu_{BGD}] - \mu_B$$

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Therefore,

$$\mu_{GD} = L_D + \frac{n_1}{n_2}\,\mu_{BGD} + \mu_B$$

Figure B-2 provides a plot of background counts versus net counts for U-238, Ra-226, and Th-232 for one of the NaI systems. (The data used in the plots are given in Table B-1.) The figure demonstrates a linear relationship between the two quantities over the range of radionuclide concentrations of interest (i.e., from background concentrations to concentrations on the calibration pad). Therefore, a simple linear relationship between background and net counts can be used to express background counts in terms of L_D

$$\mu_{BGD} = d\,L_D + e$$

Substituting the expressions for μ_{GD} and μ_{BGD} into Eq. B-3 and performing some algebraic manipulations gives

$$L_D^2 - L_D\left\{k^2 + 2\,L_C + k^2 d\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right)\right\} + L_C^2 - k^2\sigma_{N0}^2 - k^2 e\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right) - k^2\mu_B = 0 \qquad \text{(B-4)}$$

Letting

$$b = -\left\{k^2 + 2\,L_C + k^2 d\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right)\right\}$$

and

$$c = L_C^2 - k^2\sigma_{N0}^2 - k^2 e\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right) - k^2\mu_B, \qquad \text{(B-5)}$$

Eq. B-4 can be written as

$$L_D^2 + b\,L_D + c = 0$$

For which (using the solution to a quadratic equation)

$$L_D = 0.5\,[-b \pm (b^2 - 4c)^{0.5}] \quad \text{(B-6)}$$

which is an expression for the detection limit for the NaI systems. Note that L_D is a net signal ($\mu_{ND} = L_D + \mu_B$).

When the blank is not well know, the expression for c can be simplified somewhat. For the NaI systems,

$$\mu_B = \mu_{G0} - \frac{n_1}{n_2}\mu_{BG0} \quad \text{(B-7)}$$

Also, from Eq. B-1, $k^2\sigma_{N0}^2 = 0.5\,L_C^2$.

Making these substitutions in Eq. B-5, substituting for L_C (using Eq. B-2), and simplifying gives

$$c = k^2\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right)(\mu_{BG0} - e) \quad \text{(B-8)}$$

If μ_{BG} is a constant (not a function of the net counts), d = 0 and e = μ_{BG0}. In this case, c = 0. From Eq. B-6, with c = 0, L_D = -b (ignoring the root L_D = 0). Also, when d = 0, b= $-(k^2 + 2L_C)$. Therefore,

$$L_D = k^2 + 2L_C$$

which is Currie's Eq. 13, the expression commonly used to determine L_D. Therefore, the solution to Eq. B-4 is given by Currie's equation when μ_{BG} is a constant and the blank is not well known.

When the blank is well known, $L_C^2 = k^2\sigma_{N0}^2$. Substituting this quantity and the expression for μ_B given in Eq. B-7 into Eq. B-5 yields

$$c = -k^2 e\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right) - k^2\mu_{G0} + k^2\mu_{BG0}\frac{n_1}{n_2}$$

Minimum detectable concentrations (MDCs) can be determined by using the value of L_D obtained from Eq. B-6 in the appropriate calibration equation, assuming that the net counts for the other radionuclides equal those values obtained on the pad when no sources are present. Note that because L_D is determined relative to a blank, the use of a blank that has a significant concentration of the radionuclide of interest will result in the underestimation of the actual minimum detectable concentration for the radionuclide.

Table B-1. Data for Background Counts and Net Counts for a NaI System[a]

Radionuclide[b]	Sources Used[c]	Net Counts (4 s)	Background Counts[d] (4 s)
U-238	None	-15.29	81.33
	45 U-238	354.15	245.77
	25 U-238	211.14	178.39
	13 U-238	170.86	156.20
Th-232	None	28.68	2.15
	45 Th-232	492.47	26.78
	25 Th-232	310.07	17.03
	13 Th-232	266.22	13.67
Ra-226	None	3.50	11.33
	45 Ra-226	675.96	126.62
	25 Ra-226	413.41	72.35
	13 Ra-226	335.75	55.61

[a]Results were obtained using the RSS2 on 25 April 2002, with a 300-s acquisition period. Counts were converted to a 4-s period for this table.

[b]The radionuclide listed indicates the region of interest for which the net counts are specified.

[c]The number of sources used in the calibration pad was varied to produce the results shown. The number of sources used was 45, 25, 15, and 0 (none), with 45 being the maximum number of sources that the pad is designed to accommodate.

[d]Background counts are not adjusted for differences in the number of channels in the region of interest and the background regions.

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Fig. B-1. NaI Spectrum Showing Regions of Interest (ROI) and Flanking Background Regions

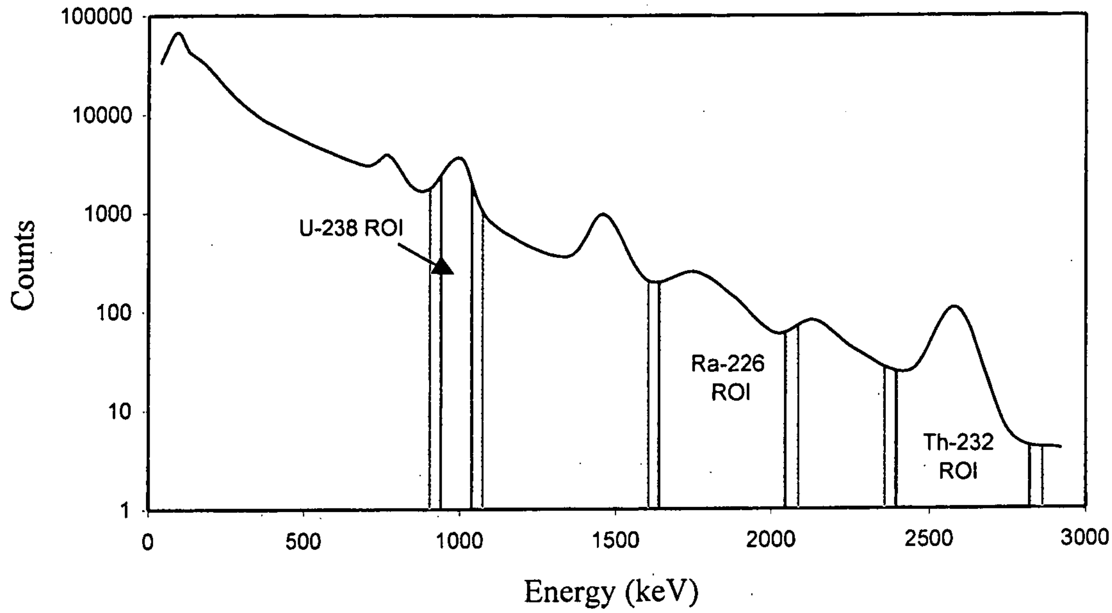

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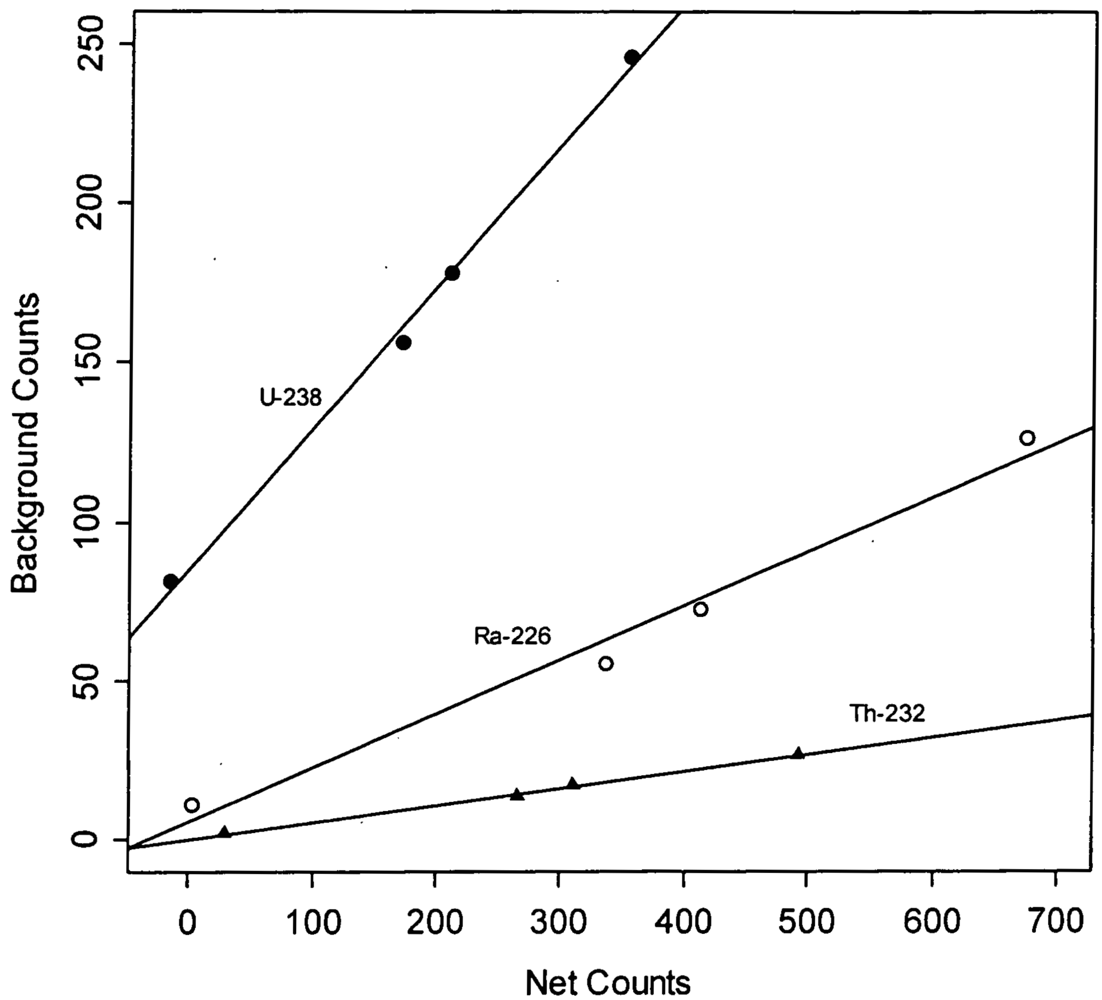
Figure B-2. Relationship Between Background Counts and Net Counts for a NaI System. The plot shows 4-s counts obtained using the RSS2 on 25 April 2002.[*]



[*]For U-238, $y = (0.445 \pm 0.018)\,x + (85.3 \pm 3.9)$, $R^2 = 0.997$.
For Ra-226, $y = (0.170 \pm 0.017)\,x + (5.6 \pm 7.1)$, $R^2 = 0.982$.
For Th-232, $y = (0.053 \pm 0.002)\,x + (0.3 \pm 0.6)$, $R^2 = 0.997$.
Standard errors are given along with the estimated coefficients.

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APPENDIX C: DATA

Table C-1. Calibration Coefficients for the NaI Systems[a]

System	F1	F2	F3	F4	F5	F6	F7	F8	F9
RTRAK	4.031	0.577	0.549	-0.016	0.143	0.070	-0.001	0.002	0.090
RSS1	3.965	0.663	0.101	-0.014	0.150	0.077	-0.001	0.003	0.078
RSS2	3.755	0.376	-0.568	-0.013	0.130	0.071	-0.001	-0.001	0.081
EMS	4.675	0.727	-0.535	-0.013	0.144	0.075	-0.001	0.001	0.082

[a]Determined using count data in Table C-3. Units are in pCi/g per net counts per second.

Table C-2. Numbers of Channels Used in the NaI Systems[a]

Radionuclide	n_1	n_2
U-238	18	12
Ra-226	69	12
Th-232	73	12

[a]n_1 is the number of channels in the ROI. n_2 is the number of channels in the background regions.

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Table C-3. Count Data[a]

		Counts[c]					
ID	Source[b]	U ROI	U Bkg	Ra ROI	Ra Bkg	Th ROI	Th Bkg
			RTRAK (Detector. No. 516, 11 March 2002)				
872.chn	U	51216	27543.0	9326	7170.2	3026	1119.3
874.chn	Ra	62632	68836.5	99145	56999.8	7497	6636.9
873.chn	Th	52023	54229.5	31510	47058.0	44577	12476.9
871.chn	None	8236	8467.5	4449	4841.5	2667	973.3
			RSS1 (Detector No. 072198C, 30 May 2002)				
730.chn	U	54229	30091.5	10782	8274.2	3768	1216.7
734.chn	Ra	58576	65586.0	94848	53492.2	8087	7488.6
728.chn	Th	59861	57934.5	33470	51244.0	50596	12793.2
727.chn	None	9161	9357.0	5820	5479.8	3428	1228.8
			RSS2 (Detector No. 072198A,30 May 2002)				
297.chn	U	54500	28911.0	11056	8699.8	3656	1289.7
301.chn	Ra	57065	61975.5	96201	49841.0	8643	6357.1
295.chn	Th	63699	57250.5	32968	50410.2	47884	12738.5
294.chn	None	9116	9451.5	5906	5824.8	3186	1277.5
			EMS (Detector No. 518, 29 April 2002)				
81.chn	U	52896	32413.5	10046	8124.8	3468	1387.0
83.chn	Ra	58049	64900.5	93760	51451.0	8061	6904.6
82.chn	Th	59005	52842.0	31146	47564.0	47316	12221.4
80.chn	None	8292	8535.0	4899	4663.2	3046	1289.7

[a]All counts were made with a 300-s acquisition period.

[b]U, Ra, and Th indicate that the uranium, radium, and thorium sources were used, respectively. “None” means that only blanks were used.

[c]U ROI, etc., provide total counts for the ROI. U Bkg, etc., provide total counts for both the low and high background regions associated with the ROI, multiplied by the ratio n_1/n_2 (see Table C-2) to adjust for differences in the number of channels used in the ROI and the background regions.

APPENDIX D: EXAMPLE CALCULATIONS

D.1 WAC TRIGGER LEVEL

The trigger level is given by Eq. A-1:

$$\text{Trigger} = L - k\sigma_{WAC} \qquad \text{(A-1)}$$

The standard deviation in the uranium concentration (in ppm) is given by Eq. A-5:

$$\sigma_{Uppm} = \frac{3}{\sqrt{T_0 T_1}} [F_1^2 V_U + F_2^2 V_{Ra} + F_3^2 V_{Th}]^{0.5} \qquad \text{(A-5)}$$

The standard deviation can be evaluated at the WAC level (1030 ppm) and substituted into the Eq. A-1 to give the WAC trigger.

In Eq. A-5, the V's are given by $V = \mu_G + \left(\frac{n_1}{n_2}\right)^2 \mu_{BG}$

Using the 300-s counts for the RTRAK (3/11/02 calibration, see Table C-3) with the uranium sources on the pad (Table C-3):

For U-238, $V_U = 51216 + (18/12)^2 (12/18) (27543) = 92{,}531$

For Ra-226, $V_{Ra} = 9326 + (69/12)^2 (12/69) (7170.2) = 50{,}555$

For Th-232, $V_{Th} = 3026 + (73/12)^2 (12/73) (1119.3) = 9{,}835$

Note that the background counts in Table C-3 have already been multiplied by n_1/n_2, so they need to be multiplied by n_2/n_1 in the preceding calculation.

$T_0 = 4$ s, $T_1 = 300$ s, $F_1 = 4.031$, $F_2 = 0.577$, and $F_3 = 0.549$. Substituting these values into Eq. A-5, along with the values for the V's gives

$\sigma_{Uppm} = \sigma_{WAC} = 106.9$ ppm.

Therefore, Trigger = $L - k\sigma_{WAC} = 1030 - (1.645)(106.9) = 854$ ppm (for a 4-s count).

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D.2 MDC

To provide an example of how the results in Section 3.0 were obtained, details of the calculations of L_C, L_D, and MDC for uranium for the 11 March 2002 calibration of the RTRAK are provided.

Calculation of L_C.

Use Eq. B-2:

$$L_C = \sqrt{2}\ k \left[\mu_{G0} + \left(\frac{n_1}{n_2}\right)^2 \mu_{BG0}\right]^{0.5} \qquad \text{(B-2)}$$

$k = 1.645$; $n_1 = 18$ and $n_2 = 12$ for U-238.

μ_{G0} and μ_{BG0} in Eq. B-2 can be determined using the count data from the 11 March 2002 calibration of the RTRAK (Table C-3):

$\mu_{G0} = (4/300)(8236)$ (Counts for U-238 ROI, no sources on pad, adjusted to 4 s.)

$\mu_{BG0} = (4/300)(8467.5)(12/18)$ (Counts in background channels without adjustment for number of channels, no sources on pad, adjusted to 4 s.)

Substituting the values for the various quantities into Eq. B-2 gives $L_C = 38.9$.

Calculation of L_D.

Use Eq. B-6:

$$L_D = 0.5\,[-b \pm (b^2 - 4c)^{0.5}] \qquad \text{(B-6)}$$

From Appendix B,

$$b = -\left\{k^2 + 2\,L_C + k^2 d\left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2}\right]^2\right)\right\}$$

Also, from Appendix B, for the case when the blank is not well known:

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$$c = k^2 \left(\frac{n_1}{n_2} + \left[\frac{n_1}{n_2} \right]^2 \right) (\mu_{BG0} - e)$$

d and e are the coefficients in the equation $\mu_{BGD} = d\ L_D + e$, which is based on the linear relationship between background and net counts (Appendix B, Figure B-2). These coefficients can be determined using the available count data because the background and net counts are known for two points, namely when the uranium sources are in place on the pad and when no sources are on the pad. The following table summarizes the data for the 300-s count for the 11 March 2002 calibration of the RTRAK and provides calculated values for a 4-s count.

Condition	Gross Counts, Uranium ROI	Background Counts, Uranium	Net Counts, Uranium
U-238 sources (300 s)	51216	27543	-
No sources (300 s)	8236	8467.5	-
U-238 sources (4 s)	682.9	367.2	315.7
No sources (4 s)	109.8	112.9	-3.1

In the table, net counts = gross counts – background counts.

The slope, d, is given by

$$d = (n_2/n_1)\ (\text{change in background counts})/(\text{change in net counts})$$

Note that the factor n_2/n_1 must be included because background counts have already been multiplied by n_1/n_2.

So, d = (12/18) (367.2 - 112.9)/(315.7 - (-3.1)) = 0.532

The intercept of the line, e, can be determined using

$$e = \text{background counts with no source} - d\ (\text{net counts with no source})$$

So, e = (12/18)(112.9) - (0.532)(-3.1) = 76.9

Therefore, $\mu_{BGD} = 0.532\ L_D + 76.9$, in counts in a 4-s acquisition period.

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All of the quantities needed to determine b are now known and can be substituted into the expression for b given above to yield a value for b of –85.8.

To determine c, the value of μ_{BG0} is needed also. From the table above, the value is (12/18)(112.9) (background counts with no sources on pad, adjusted by n_2/n_1). Substituting values into the expression for c yields a value for c of -16.7.

Now that b and c are known, L_D can be determined using Eq. B-6:

$$L_D = 0.5[-(-85.8) \pm ((-85.8)^2 - 4(-16.7))^{0.5}]$$

$$= -0.19 \text{ or } 86.0.$$

L_D is positive, therefore, its value is 86.0.

Calculation of MDC.

The MDC is determined using the calibration equation for U-238 (see Sec. 3), converted to provide a uranium concentration in ppm (3*U-238 specific activity):

$$U = 3\,[F_1\,U_{NCR} + F_2\,Ra_{NCR} + F_3\,Th_{NCR}]$$

From the 11 March 2002 calibration of the RTRAK, $F_1 = 4.031$, $F_2 = 0.577$, and $F_3 = 0.549$ (see Table C-1).

As noted in Section 3, the MDC is determined with U_{NCR} equal to the net count rate corresponding to L_D for uranium and with Ra_{NCR} and Th_{NCR} equal to the values obtained on the pad when no sources are present.

Therefore, the MDC for total uranium in ppm is

$$U_{MDC} = 3((4.031)(86.0/4) + (0.577)(-5.2/4) + (0.549)(22.6/4)) = 267$$

The counts are divided by 4 s to convert to a count rate. The net counts for Ra-226 (-5.2) and Th-232 (22.6) are obtained in the same manner as shown in the table above for uranium (-3.1) when no sources are on the pad.

The MDC of 267 ppm is a wet-weight concentration. For the pad, the wet-weight and dry-weight concentrations are equal; however, in the field that generally is not the case. Assuming a moisture level of 26% (which corresponds to a moisture correction factor of 1.26), the MDC on a dry-weight basis is 337 ppm.

Therefore, U_{MDC} = 337 ppm (dry-weight) for a 4-s count. For an 8-s count (or any other counting period), the MDC can be determined following the same approach as used for a 4-s count. The result is an 8-s MDC of 234 ppm (dry weight). Note that the result is

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approximately the same as would be obtained by dividing the 4-s MDC (337 ppm) by the square root of two, which yields 238 ppm. (Such an approximation does not work well for Ra-226 because of the effects associated with the use of a Ra-226 correction.)

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